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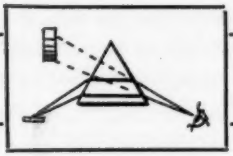

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ON THE INTENSITY OF ILLUMINATION IN SPECTROGRAPHS

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ABSTRACT

The *intensity of illumination* of the spectrum from a concave grating is computed. The customary arrangements are compared of which some correct the astigmatism of the spectral lines (sections 1–6). A cylindrical lens in front of the plate, as suggested by Humphreys and Gehrcke, seems to be the only device that increases the intensity without reducing dispersion and resolving power. Thus for a small spectral range a reduction of the time of exposure to 1/24 has been realized without any loss of resolving power (section 6). The bearings of the results on the spectra from the grating at grazing incidence (vacuum spectrograph), the plane grating and the prism are discussed (sections 7–9). The main results are checked by experiments.

Introduction

The problem of photographing the spectrum of a faint source of light from a large concave grating led to a systematic study of the intensity of illumination produced by different arrangements. The aim was to produce the highest intensity of illumination while preserving the full dispersion and resolving power of the original mounting. Since no discussion of the problem could be found in the literature, the results are briefly given in the present paper.

It is known that a spectral line formed by a concave grating in the ordinary mounting is an astigmatic image of the slit; light from any point in the slit being brought to a *vertical* focal line on the plate and to

a *horizontal* focal line at some distance beyond the plate. This is true for the usual mountings given by Paschen and Runge, Rowland, and Eagle. If a very short slit is used, this astigmatism involves a considerable loss of intensity, since the light is spread over the long vertical range of the spectral line. (It is assumed that the slit and the rulings of the grating are vertical.) As the length of the slit is increased, the *lengths* of the spectral lines, as well as the *intensity of illumination* in their central regions, are increased. This increase of illumination continues until a critical length of the slit is reached.[1] Points of the slit beyond a certain distance from the optical axis do not contribute to the illumination of the middle of the spectral line. In this reasoning it is assumed that the source of light is large enough to cover the slit.

There are several arrangements to correct the astigmatism. In this paper, the intensity of illumination on the photographic plate will be derived for the following arrangements: (1) The device of Runge and Mannkopff, who correct the astigmatism by illuminating the slit with astigmatic light formed by a cylindrical lens in front of the slit. (2) The ordinary mounting, the source of light being directly in front of the slit. (3) The ordinary mounting, with a spherical lens to focus the light from the source on the slit. (4) Placing the source of light in the "outer focus" of the grating. (5) Placing a cylindrical lens between the slit and the grating. (6) Placing a cylindrical lens between the grating and the photographic plate. (7) The vacuum spectrograph-grating at grazing incidence. (8) The plane grating or echelon—spectrographs that produce straight, stigmatic, spectral lines. (9) The prism spectrograph.

1. The Cylindrical Lens Between the Source of Light and the Slit

Runge and Mannkopff[2] corrected the astigmatism due to the concave grating by forming an astigmatic image of the source of light on the slit. Their optical system consists of a spherical and a cylindrical lens. This system places the vertical focal line of the astigmatic bundle of rays at the slit. The grating then forms a stigmatic image of the source—not of the slit—on the photographic plate. The slit, grating, and plateholder remain unchanged. This discussion deals only with that property of the grating concerned with the formation of astigmatic images. It will, therefore, be sufficient to consider the grating equivalent to a lens,

[1] C. Runge in H. Kayser: Handbuch der Spektroskopie, *I*, p. 464; E. C. C. Baly: Spectroscopy, 3d Edition, *I*, p. 165.

[2] C. Runge and R. Mannkopff: ZS. f. Phys., *45*, p. 13; 1927.

whose focal length is different in the horizontal and vertical planes. The diagram will, on that account, not show the angle between the incident and reflected beams at the grating. The action of the grating in focusing the light, in the two planes, is shown in Fig. 1. C is a lens having cylindrical, as well as spherical, properties.

In general, for a system of spherical lenses the intensity of illumination dL'/da' in the plane of the image is given[3] by the equation $dL'/da' = k/\beta^2(dL/da) = k\pi I\, u^2/\beta^2$ where dL is the quantity of light entering the entrance pupil; da, the element of surface of the source of light; k, an attenuation factor to represent losses by absorption and reflection, β, the linear magnification, I = the intrinsic intensity of the source, u, the aperture of the system (angle seen from the source). Only small

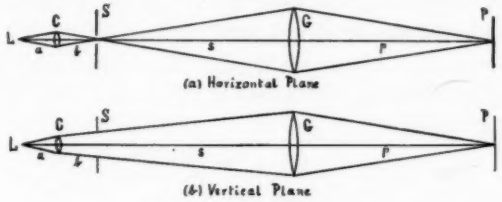

FIG. 1. *Spectral line is a stigmatic image of source of light.* (*Runge and Mannkopff*). L, source of light; C, spherical-cylindrical lens; S, slit; G, grating; P, plate; a, b: distance CL and CS; s, p: distances GS and GP.

apertures will be considered. Even without this formula it is clear that, for any given source, the illumination will be proportional to the total light energy admitted by the entrance pupil (proportional to u^2) divided by the area over which this energy is spread (proportional to $1/\beta^2$). In the following comparison of different systems the factor $k\pi I$ will be omitted. In the present problem, which involves different apertures and magnifications in the two planes (cf. Fig. 1), the illumination must be expressed as the product of two different factors, instead of the square of only one.

The slit will be narrower than the image of the source L formed by the lens C. In the horizontal plane, therefore, it will be sufficient to consider the intensity on the slit, since this corresponds once for all to a certain horizontal concentration of light on the plate P.

In the expression for the intensity of illumination, the factor which represents the horizontal plane is $u_h/\beta_h = (C_h/a)\ (a/b) = C_h/b$. (Capital letters indicate the linear dimensions of lenses, images, or slit; and small

[3] M. von Rohr: *Optical Instruments*, London, 1920, p. 550.

letters refer to the distances indicated in Fig. 1. The subscript h refers to the horizontal plane.) The diameter of the lens C is so chosen as to fill the entire grating with light, so that $u_h/\beta_h = C_h/b = G_h/s$ where G_h is the apparent horizontal diameter of the grating. It follows that under this condition the horizontal factor of intensity is given by the grating and its mounting, and is independent of the lens C.

In all arrangements to be discussed, the horizontal component will be represented by Fig. 1a or, still simpler, the source will be directly in front of the slit which leads to the same formula. As in any case the horizontal factor of the intensity will not depend on the lenses, this factor will be left out of the discussion, subsequent considerations being limited to the vertical plane. The subscripts will be omitted.

The factor representing the intensity of illumination in the vertical plane is found by an elementary calculation to be $J = u/\beta = G/p$. If the lens C is so chosen as to fill the grating with light, the contribution in the vertical plane is also independent of the diameter and corresponding position of the lens C.

2. The Source of Light Placed Directly in Front of the Slit

A comparison is made between the intensity of illumination obtained in the case just discussed involving the use of a cylindrical lens in front of the slit with that obtained in the ordinary mounting when an extended source of light is placed directly in front of the slit, without a focussing lens. The *horizontal* plane contributes to same factor as in (1).

The light from an element ds of the slit, in the *vertical* section, is brought to focus in F, far behind the photographic plate P, on which the vertical focal line is produced. The energy emitted by ds will, therefore, spread over a considerable part of the spectral line at P, and neighboring elements of the slit will contribute light into the same part of the line. This line will have a maximum of intensity in a limited region about the optic axis, beyond which, in both directions, the light fades away. Only a limited part of the slit, however, is in a position to contribute to this maximum value of the illumination. The dotted line in Fig. 2 indicates the limiting case in which ds just barely contributes light to the center of the spectral line at P. This limit defines the effective length of the slit. The contribution from ds must be integrated over the effective length. The result states the maximum intensity of illumination at the center to be $J = G/p$. (The same result can easily be obtained from a general theorem in geometric optics, as will be shown in section (8).) This

value of the intensity is the same as that obtained with the stigmatic mounting discussed in section (1).

3. The Source of Light Focused by a Spherical Lens on the Slit

In many instances, e.g., in the investigation of the Zeeman effect, the source of light is smaller than the effective length of the slit. In addition, it is often impossible to bring the source close to the slit. It is then customary to focus an image of the source on the slit by means of a spherical lens. When the image is enlarged sufficiently to cover the effective length of the slit, a simple calculation again leads to the result $J = G/p$ which is identical with the results of sections (1) and (2). Thus there is no loss of light due to the small dimensions of the source. This does not hold for stars, however, whose images are not defined by geometrical optics but by diffraction.

If, on the other hand, the image of the source is not large enough to cover the effective portion of the slit, there will be a corresponding loss of intensity on the plate.

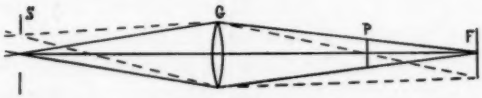

FIG. 2. *Effective length of the slit (vertical plane).* S, slit; G, grating; P, plate and inner focus; F, outer focus.

The principal result is that the use of a cylindrical lens to set aside the astigmatism of the grating, as shown by Runge and Mannkopff, does not produce a greater intensity of illumination on the plate than is obtained with the usual focusing methods, provided always that the effective length of the slit is filled with light. This has actually not been the aim of the authors. They merely wanted to produce spectral lines as stigmatic images of the source—not of the slit—to compare the spectra emitted from different parts of the same source. This arrangement also minimizes scattering within the spectrograph, since only such light as contributes to the spectral lines is admitted through the slit.

4. The Source of Light in the Outer Focus of the Grating

The middle of the spectra line receives light from the whole effective length of the slit. When we reverse the path of the light placing a point source (emitting monochromatic light of the appropriate wave length)

at the point where the middle of the spectral line would normally appear, the grating will form a vertical focal line thereof at the slit, just covering its effective length, and a horizontal focal line beyond the slit. This may be called the outer focus. In order to produce full intensity of illumination on the plate, the source of light must cover either of those two foci. In sections (2) and (3), the *vertical* focal line at the slit was covered by the source (or an image thereof). It has been suggested[4] to cover the *horizontal* outer focal line instead, for instance with a horizontal Geissler tube. This device is admissible from the point of view of geometric optics. Wave considerations bar it nevertheless, since different parts of the grating would receive light from different parts of the source. Such rays would not be coherent and would diminish the resolving power.

This disadvantage may be removed by placing the source at the outer focus of the grating, and by forming a vertical line focus of the source on the slit with a *cylindrical* lens. The grating will then be the only focussing agent for rays in the vertical plane. This arrangement is shown in Fig. 1 if L is assumed to be coincident with the outer focus of the grating and if C is a cylindrical lens without any spherical properties; in Fig. 1b C would be a plane parallel plate.

The calculation of the intensity of illumination on the plate again leads to the result $J = G/p$, as before. This arrangement, involving only a cylindrical lens, may be considered as a special case of the Runge-Mannkopff arrangement.

For a *small source of light*, the comparison of this mounting (the source in the *outer focus*, focused on the slit by a *cylindrical* lens) with the ordinary mounting (the source focused on the slit by a *spherical* lens without much enlargement) leads to a curious result. With the customary spherical lens the intensity of illumination on the plate is greatly reduced by the astigmatism spreading the energy over a long spectral line. The same faint intensity will be obtained by placing the small source immediately in front of the slit. If instead the small source is placed at the outer focus of the grating (several meters distance from the slit for a large grating) and only its horizontal coordinate is focused on the slit by a cylindrical lens, the spectral lines will have the full value of intensity as in the cases (1)–(4), but they will be very short. The reason is that only in the latter arrangement the spectral lines are monochromatic *stigmatic* images of the source. Instead of the cylindrical lens, the arrangement of Runge and Mannkopff (section 1) may be used. This

[4] E. von Angerer, Handbuch der Experimentalphysik, *21*, p. 301.

comparison applies to stellar spectra; instead of the source, a stigmat image of the source is to be placed at the outer focus.[5]

This result has been checked by an experiment. The line 5791 of the mercury arc was photographed with three different arrangements: (1) the arc focused full size on the slit, (2) an enlarged image of a small area of the arc formed on the slit by a lens of a sufficient diameter to fill the grating with light, (3) the arc placed at the outer focus of the grating (distance from the slit 550 cm), a cylindrical lens with vertical axis forming an astigmatic image on the slit. In all three cases the blackening of the plate was practically the same. A shorter slit, however, gave considerably smaller intensity.

5. A CYLINDRICAL LENS BETWEEN THE SLIT AND THE GRATING

This discussion hitherto has involved no changes in the construction of the spectrograph proper. The only changes of apparatus have been concerned with the focusing of light from the source on the slit. Runge and Paschen[6] used a mounting in which the intensity of the spectral lines increases fourfold and the dispersion is halved. They made the light from the slit parallel by a collimating lens in front of the grating. The effects are analogous to those brought about by reducing the focal length of the camera lens in a prism spectrograph. An arrangement producing a similar effect has been constructed by *Meggers and Burns*[7] who produce parallel light by reflection from a concave mirror. This discussion, however, does not deal with these mountings, because the present problem is to increase the intensity of illumination without sacrificing dispersion.

It remains to discuss two further arrangements which remove the astigmatism by a cylindrical lens with its axis horizontal *inside* the spectrograph. Rays in the horizontal plane are not affected except by the negligible effect of the lens acting as a thin plane parallel plate. For rays in the vertical plane, the cylindrical lens adds sufficient focusing power to the grating to bring the horizontal focal line into coincidence with the vertical focal line on the photographic plate. The focal length and position of the cylindrical lens must be suitably chosen.

[5] The adjustment depends upon the wave length. This dependence, however, can be partly compensated by the chromatic error of the lenses. Cf. C. Runge and R. Mannkopff, ZS. f. Phys. *45*, p. 24; 1927.

[6] Runge and F. Paschen, Wied. Ann., *61*, p. 644; 1897.

[7] W. F. Meggers and K. Burns, Scient. Pap. Bur. of Stand. *18*, p. 185; 1922. For other references cf. E. v. Angerer, Handbuch der Experimentalphysik, *21*, 311.

As the light leaving the grating spreads by dispersion over a wide angle, it appears to be simpler at first sight to place the cylindrical lens between the slit and the grating. The calculation of the intensity of illumination on the photographic plate once again leads to the same result $J=G/p$. The cylindrical lens will collect more light from the slit than the grating alone due to an increase in aperture, but it will spread the light over a larger area, since it enlarges the vertical component. This arrangement produces the same effect as the cylindrical lens in front of the slit, by giving rise to a stigmatic image of the source without, however, increasing the intensity of illumination on the plate.

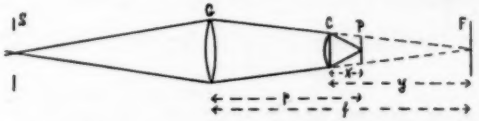

FIG. 3. *Cylindrical lens between grating and plate (vertical plane).* S, slit; G, grating; C, cylindrical lens; p, plate; F, outer focus. x, y: distances CP and CF; p, f: distances GP and GF.

When the source of light is not directly in front of the slit, but is focussed on the slit by a spherical lens of proper aperture, the magnification can be changed, but the intensity on the plate remains unaltered.

6. A CYLINDRICAL LENS BETWEEN THE GRATING AND THE PLATE

A striking success has been reported by Humphreys and by Gehrcke.[8] A cylindrical lens, with its axis horizontal, was placed directly in front of the plate. As a powerful cylindrical lens Gehrcke used a glass rod bent around the Rowland circle immediately in front of the plate. This arrangement is like that of section (5), except that the cylindrical lens is moved to the other side of the grating.

In order to obtain the full intensity, the vertical diameter of the cylindrical lens must be $C=Gy/f$. Under this condition, the intensity of illumination on the plate is computed to be $J=(G/p)\cdot(p/f)\cdot(y/x)$

[8] W. J. Humphreys, Astroph, J., *18*, p. 324; 1903; ZS. f. Instr. Kde, *31*, p. 217; 1911. E. Gehrcke, ZS. f. Instr. Kde, *31*, pp. 87 and 217; 1911. E. Gehrcke and E. Lau, Ann. d. Phys., *76*, p. 679; 1925. Cf. H. A. Rowland, Physical Papers, 489. Humphreys describes an arrangement in which the intensity of illumination is increased by means of mirrors fastened to the slit. These mirrors produce an apparent prolongation of the slit. This device is useful only if the effective length of the slit is not filled with light. In general, except for stellar spectra, it will be easier to fill the slit with light by means of some focusing device rather than of these mirrors. When used near the photographic plate, these mirrors have an effect. The increase of intensity can, however, never exceed the factor 3, since each mirror adds only once the original intensity.

This differs from the previous result by the factor $(p/f) \cdot (y/x)$. The fraction y/x may be made very large for a cylindrical lens of short focal length. This formula—as all others of this discussion—holds only for small values of the aperture. As the position of the cylindrical lens is taken nearer the grating, ($x=p$ and $y=f$), the intensity of illumination approaches the normal value G/p.

The intensity of illumination has been calculated for the actual case of a 21-foot grating, the angle of incidence being 45°, for the wave length 3064A in the second order. A cylindrical lens, whose focal length is 30.5 and whose diameter must not be smaller than 4 cm, will increase the intensity of illumination by the factor 16. This calculation is confirmed by the experimental results reported by Gehrcke. Another example will be discussed below.

This increase in the intensity of illumination is due to the removal of the astigmatism and the concentration of the large into a small image, without altering the aperture of the system G/s. The effect of the cylindrical lens in a given position will be restricted to a limited range of wave lengths.

It must not be concluded that this large intensity of the *stigmatic* image of the slit is necessarily the maximum value obtainable. It will be shown in section (8)—and it can be seen in a simple experiment—that a previously *stigmatic* image of the slit is made more intense by a cylindrical lens to concentrate the light, thereby making the image astigmatic in the vertical plane. For the ordinary mounting of the concave grating, however, the example just discussed gives spectral lines so short that a further concentration of light does not seem advisable.

The cylindrical lens, concentrating the vertical coordinate only, does not change the *dispersion*. The question arises, if the *resolving power* is not impaired by inserting a lens. This cannot safely be judged from the few spectra published,[9] because they do not show a narrow structure. Therefore the resolving power was investigated, using a first quality cylindrical lens[10] with a 21-foot grating, a source of light with the sharpest lines obtainable and a fine grain plate. The lens was carefully adjusted with the axis of the cylindrical surface normal to the beam of light and the spectral lines; the plateholder was slightly readjusted. The absorption spectrum of molecular iodine (molecular weight 254) at room

[9] E. Gehrcke and E. Lau, Ann. d. Phys. *76*, p. 679; 1925.

[10] 5×5 cm; $f=21.5$ cm. The lens was made by C. P. Goerz, American Optical Company, New York City. I understand that the cylindrical lenses manufactured by this company for technical purposes are tested with interference methods.

temperature and low pressure (0.2 mm) was photographed on process plates. With the adjustment discussed above—the astigmatism completely removed—spectrum (a) of Fig. 4 was photographed in 10 seconds. The comparison with the spectrum taken without the cylindrical lens (Fig. 4b), photographed in 240 seconds, proves that for the middle of the spectral lines the resolving power is fully maintained over a small range of about 1 cm of the spectrum. When, however, the cylindrical lens was shifted only a few centimeters towards the photographic plate so that the astigmatism was not quite completely removed, the full resolving power was maintained over a range of several centimeters of the plate (Fig. 4c compared with 4d) with an exposure of 20 seconds. Thus for a small range of the spectrum a reduction of the time of exposure to 1/24, for a larger range a reduction to 1/12 has been realized without any loss of resolving power.

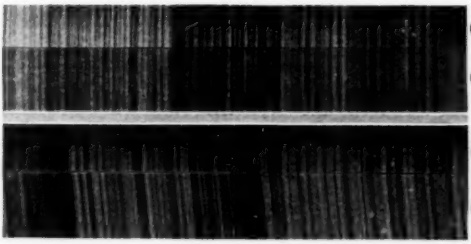

FIG. 4. *Comparison of resolving power of concave grating with and without cylindrical lens removing the astigmatism (absorption spectrum of iodine vapor; 7 times magnified; positive (a) Astimatism removed; 10 sec. exposure; (c) Astigmatism not completely removed; 20 sec. exposure; (b), (d) Spectra taken without the cylindrical lens; 240 sec. exposure.*

Dr. G. B. Kistiakowsky informs me that he failed to obtain the full resolving power using a cylindrical lens *parallel to the plate* which was tilted against the beam of light, as described by previous authors. Evidently it is important to adjust the lens carefully *normal to the beam of light.*

7. GRATING AT GRAZING INCIDENCE—THE VACUUM SPECTROGRAPH

Some very successful vacuum spectrographs have been constructed to utilize the advantage of the high reflecting power of a metal or glass at grazing incidence. The slit, grating, and plate are fixed along a short range of the Rowland circle.[11] This arrangement has the great disad-

[11] J. H. Osgood, Phys. Rev., *30*, p. 567; 1929. M. Sieghahn and T. Magnusson, ZS. f. Phys., *62*, p. 435, 1930.

vantage that the astigmatism spreads the light over an image of great length. In an instrument in this laboratory (2 m grating, height 5 cm, angle of incidence 6.3°, wave length about 350A), the light from a hot spark, about 0.5 mm in length, spreads over a spectral line 185 mm long, i.e., about 370 times the length of the source. Since no cylindrical lens can be used here, the astigmatism may be removed by a concave mirror whose axis is perpendicular to that of the grating.[12]

This use of a mirror might produce such a gain in the intensity of illumination as to offset by far the additional losses due to imperfect reflection, which would not be large since the mirror is used at grazing incidence. A mounting of this kind would be useful only over a small range of wave lengths. It might, however, make it possible to investigate the fine structure of spectral lines in the ultraviolet with a long focus grating which would otherwise not give sufficient intensity.

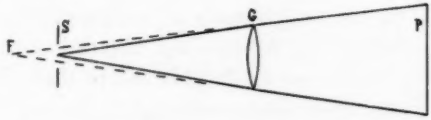

FIG. 5. *Astigmatism of the concave grating with grazing incidence. S*, slit, *G*, grating; *P*, plate and inner focus; *F*, outer focus.

In the ordinary arrangement with grazing incidence, the astigmatism gives rise to still another effect which arises from the fact that the effective length of the slit is not filled with light. The horizontal focus *F* is no longer behind the plate, but is now beyond and near the slit, as is shown in Fig. 5. This shows that in the vertical plane, the grating acts almost as a plane mirror. For a small source of light, *viz.*, a hot spark, a ruling only a *few millimeters* long will be sufficient to produce the full intensity of spectral lines of 5 mm length. Gratings with short rulings might turn out to be of better quality than others since the wear on the ruling diamond would be reduced.[13]

[12] The curvature and position of this mirror may be computed easily. It may be located arbitrarily between the grating and the plate, its function being similar to that of the cylindrical lens in the preceding section. The astigmatism of the light leaving the grating may be calculated from Runge's formulas. (C. Runge and R. Mannkopff, ZS. f. Phys., *45*, p. 14; 1927, equations (1) and (2). The same system of equations holds for a concave mirror by putting $\phi_A = \phi_B$). For an arbitrary angle of incidence, which should be chosen near grazing incidence, the same pair of equations yields the curvature of the mirror and the position of the image.

[13] Note added in proof: In a recent paper, J. E. Mack, J. R. Stehn and B. Edlen(J.O.S.A. *22*, p. 257; 1932) recommend short rulings for the grating, to be used at grazing incidence.

8. THE PLANE GRATING AND THE ECHELON

Gehrcke recommends the use of a cylindrical lens in all spectrographs giving *straight* spectral lines, including those in which the images are stigmatic without them (plane grating, echelon). The effect is seen in a simple experiment: Light from a long vertical slit, uniformly illuminated, is focussed on a screen with a spherical lens. A short focus cylindrical lens, with its axis horizontal, in front of the screen concentrates the light considerably. The maximum intensity at the center depends upon the position of the cylindrical lens. A pronounced maximum occurs when the cylindrical lens just forms an image of the spherical lens (strictly speaking, of its vertical coordinate) on the screen.

The intensity of illumination on the screen has been calculated by the method used in section (2). The source of light was considered to be directly in front of the slit. The expression for the intensity of illumination results from an integration of the effects of successive elements of the slit, each of which sends an astigmatic bundle of light to the screen. The limits of the integral are determined by the effective length of the slit, which is considerably larger than for the concave grating in the ordinary mounting, (section (2)), because a large cylindrical lens may collect light which diverges considerably from the optical axis; the effective length of the slit is governed by the vertical diameter of the cylindrical lens. The result of the calculation states that the intensity is equal to C/y, in the same units as before, C being the vertical diameter of the cylindrical lens, and y its distance from the plate.[14] This intensity is independent of the size of the spherical lens. A large lens gives a large *area* of maximum intensity, but not a large *value* of the intensity.

This result leads to the practical conclusion that the *stigmatic* image of a long slit does not necessarily represent the maximum intensity. In any actual case, this increase of the intensity on the plate is limited, because the spectral lines must have a certain minimum length.

[14] It is interesting to discuss the same problem on the basis of a general theorem in geometric optics. A diaphragm in front of a luminous screen transmits light as if it were radiating light itself with the same intrinsic intensity as the screen, independent of the distance between them. The same is true when the diaphragm is covered by a lens. The present problem is concerned with one component of an astigmatic bundle. This theorem is applied, therefore, in considering only the vertical spreading of light when the diaphragm (the grating) receiving light from a long slit is focused by a cylindrical lens on a photographic plate. The intensity of illumination on the plate turns out to be C/y, as before, provided that the slit has a certain minimum length.

9. THE PRISM SPECTROGRAPH

The question finally arises whether or not the intensity of illumination in a prism spectrograph may be improved by the use of cylindrical lenses. As Gehrcke has pointed out, since the lines formed in a prism spectrograph are curved, the blurring of their vertical coordinates by a cylindrical lens entails a broadened line. An improvement may be found nevertheless.

The success of the cylindrical lens in front of the plate with the concave grating is due to the fact that the stigmatic spectral line is a *reduced* image of the slit in the *vertical* plane, and a *full-size* image in the *horizontal* plane (the dispersion being unimpaired). The same effect may be realized in the prism spectrograph by replacing both the collimating lens and the camera lens by cylindrical lenses having vertical axes. Sharp spectral lines are thus produced, which are stigmatic in the horizontal plane, but pronouncedly astigmatic in the vertical plane.

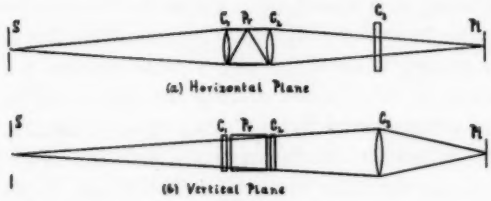

FIG. 6. *The prism spectrograph with cylindrical lenses.* S, slit; C_1, C_2, C_3, cylindrical lenses; *Pr*, prism; *Pl*, plate.

Another cylindrical lens, with its axis horizontal, placed *nearer the plate*, will then bring the vertical focus into coincidence with the horizontal focus. The reduction of the image in the vertical plane brings about an increase of the intensity. The size and focal length of the third cylindrical lens must be suited to the dimensions of the instrument. In the example of Fig. 6 the diameter of the new lens, placed midway between the camera lens and the plate, must be about 50 percent larger than that of the other lenses; the intensity will be increased by the factor 3. A simple experiment with a prism and three cylindrical lenses as in Fig. 6 shows that the spectral lines are still stigmatic, although curved, images of the slit. For the definition of the spectral lines it will be desirable to choose a long focus collimating lens C_1, in order to make the rays nearly parallel inside the prism.

The dispersion and presumably the resolving power are maintained over a certain range of wave lengths near the axis. This arrangement will

certainly not be good for general use. It might be useful, however, for a special problem in which both a large dispersion and a large intensity must be realized over a limited spectral range.

CONCLUSIONS

The spectral lines from a concave grating show the *same intensity* in the following five arrangements: (1) According to Runge and Mannkopff, an astigmatic image of the source is formed on the slit such that the spectral lines are stigmatic images of the source. (2) The source is placed directly in front of the slit. (3) The source is focused on the slit by a spherical lens so that the effective length of the slit is filled with light; this applies to a small source, too, which is magnified on the slit. (4) The source is placed at the outer focus of the grating and focused on the slit by a cylindrical lens with vertical axis. In these four cases the slit must have a certain minimum length. (5) The source is placed in front of the slit or focused on the slit by a spherical lens; the astigmatism of the grating is removed by a cylindrical lens between slit and grating. The same intensity of illumination as in these five arrangements of the *concave* grating is obtained with a *plane* grating in the ordinary mounting. Hence at the concave grating the loss of light due to astigmatism is just compensated by the superimposed effect of the whole effective length of the slit. (6) As compared with the effect of these five arrangements, a considerable *increase in the intensity* is produced by a cylindrical lens in front of the plate.

In the arrangements (1) and (4) each spectral line is a stigmatic image of the source of light but not of the slit; in (5) and (6) each spectral line is a stigmatic image of both the source of light and the slit.

For photographing the spectrum of a small source, e.g., a spark, the most effective method is as follows: a cylindrical lens in front of the plate will increase the intensity of illumination. If this lens is adjusted so that the astigmatism, due to the concave grating, is just compensated for, it will not be *necessary* to form an enlarged image of the source on the slit; this is *advisable*, nevertheless, because otherwise the spectral lines will be exceedingly short. (7) For the vacuum spectrograph, a corresponding increase in the intensity is to be expected by placing a concave mirror with grazing incidence between grating and plate removing the astigmatism. (8) For a *stigmatic* spectrum consisting of straight spectral lines—the spectrum of the plane grating or echelon—a marked increase in the intensity will be produced by a strong cylindrical lens near the plate. By this device the lines are made astigmatic. This

shows that generally the complete removal of astigmatism does not coincide with maximum intensity. Method (6) removes astigmatism and gives nearly maximum intensity. (9) For the prism spectrograph, too, the intensity on the plate can be increased within a small range of the spectrum by a suitable combination of cylindrical lenses.

The author wishes to express his appreciation to Dr. M. Grabau for his cooperation.

THERMAL BEHAVIOR OF CERTAIN SOLID SOLUTIONS*

By E. L. Nichols and Mary A. Ewer
[Cornell University, Ithaca, N. Y. Received June 3, 1932]

The present study had its origin in a chance observation made in the summer of 1931.[1] A small sample of thorium oxide, containing a trace of terbium oxide, as activator, which had been prepared in 1928[2] was in process of reignition in a quartz crucible. To hasten the operation the Bunsen burner, by means of which the crucible had been heated from below, was removed and the flame was applied from above directly upon the glowing powder. It was noticed that when the flame was withdrawn from the surface of the powder either by a bodily movement of the burner or by suddenly turning off the gas, there was a remarkable momentary glow of the powder, not synchronous with the removal of the flame but following it by an easily appreciable interval and having a perceptible duration and a characteristic color (a pure red) easily distinguishable from the rapidly vanishing incandescence of the cooling substance. Further investigation of this effect and of various related effects subsequently observed has been made by the present authors.

Method

To determine the approximate temperature at which the flash up occurred, one junction of a Pt-PtRh thermoelement was buried just below the surface of the powder in the crucible (Fig. 1). The wires of the thermoelement were protected by passing them in the usual manner through double bored clay insulating tubes. A galvanometer of suitable sensitiveness and having a quick period of oscillation (two seconds) was adequately damped by series and shunt resistances and followed the temperature fluctuations of the junction closely and promptly.

The crucible containing the cando-luminescent material (a trace of an activator, e.g., terbium oxide, in solid solution in thorium oxide) was heated from below to a dull red and the Bunsen flame was then applied from above to the upper surface of the powder. The material, hitherto inert, immediately assumed a ruddy cando-luminescence due to flame excitation. Later, as the temperature rose, this was supplanted by a

* The senior author wishes to make acknowledgement to the Heckscher Research Council of Cornell University for assistance rendered in support of this research.

[1] Nichols and Wick: Paper read at the Rochester meeting of the Optical Society of America (Oct. 1931); J.O.S.A. *22*, p. 357; 1932.

[2] Nichols and Boardman: J.O.S.A. *20*, p. 115; 1930.

brilliant pale yellow-green glow. When the latter had become well established, the flame was quickly removed or was quenched by cutting off the supply of gas. The luminescence vanished at once, to be followed a fraction of a second later by the sudden red flash-up which we desired to study.

MODE OF RECORDING

In step with the occurrence of the glow the galvanometer deflection rose sharply for several degrees and it fell with equal rapidity. Evidently the flash up was associated with a remarkable thermal disturbance of the luminescent substance.

To obtain a more definite picture of this phenomenon in its relations to time and temperature the following simple device was improvised: In lieu of the usual scale, the light-spot from the galvanometer with its marker was focused upon a chronograph drum which revolved on a horizontal axis (one revolution a minute). Around the drum was

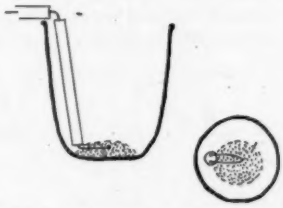

FIG. 1. *Vertical and horizontal cross-sections of the crucible, showing the thermojunction and the material under examination.*

stretched a sheet of cross-section paper, ten lines to the inch. Both temperatures and times were thus given by the position of the marker upon the paper.

After some practice it was found possible to follow the galvanometer index with a pencil throughout an entire run with an accuracy quite sufficient for our purpose. The trace thus formed had the advantage over a photographic record of being immediately available. In Fig. 2 are shown typical portions of such curves traced directly from the chronograph sheet. Subsequent diagrams are transposed for convenience into the usual form with temperatures as ordinates.

RESULTS

By the simple procedure outlined above the following facts were readily established: (1) Thorium oxide containing praseodymium or uranium as activator, instead of terbium, also showed the ruddy

luminescent glow and accompanying thermal disturbance already described. (2) Unactivated oxides (e.g., oxides of thorium, titanium, aluminum, and magnesium) showed no after flash nor thermal disturbance after heating by direct exposure to the flame: nor did any of the substances studied, whether activated or not, when they had been heated *from below only*.

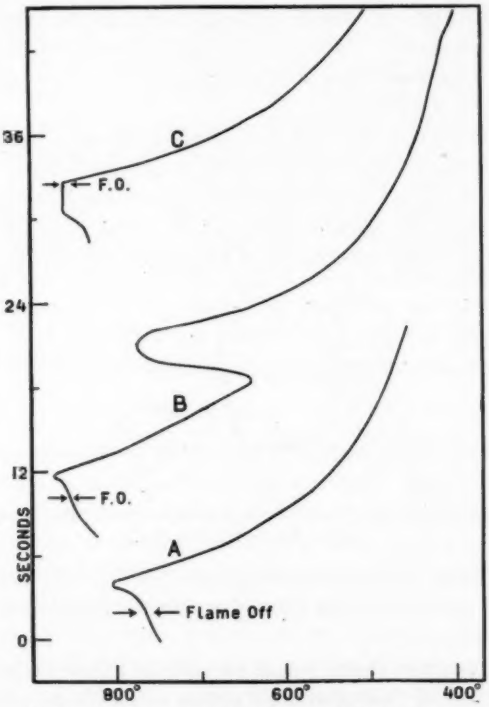

FIG. 2. *A sample sheet as it appeared when taken from the cylinder. Three cooling curves are shown, the point of removal of the flame being indicated by arrows. Abscissae represent temperatures (decreasing); ordinates represent time in seconds.*

SPECTRUM OF THE FLASH UP

Although evanescent, the momentary brightness of the luminescent glow (in the case of thorium +0.5 percent praseodymium) sufficed for observations with a hand spectroscope. During exposure to the Bunsen flame two bands were visible, 0.510μ—0.520μ (Eu) and 0.550μ—.560μ (Eu or Tb). The spectrum of the flash up on the other hand appeared to consist solely of a broad band from 0.620μ to 0.650μ.

In a recent study of calcium oxide activated by praseodymium[1] the spectrum obtained by cathode bombardment contained the bands listed above but the band in the red was double, one crest assignable to euro-

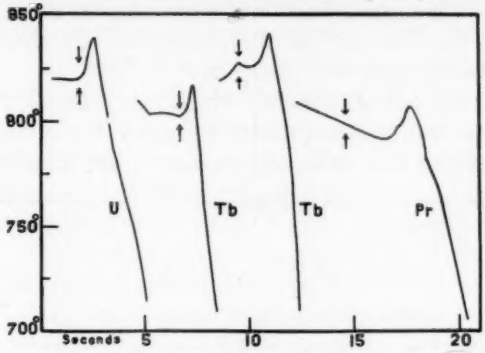

FIG. 3. *Effect I, usual form. First curve at left, small amount of uranium oxide in solid solution in thorium oxide. Next two, small amount of terbium dissolved in thorium oxide (Boardman preparation). Last curve, 0.05 per cent Pr dissolved in thorium oxide.*

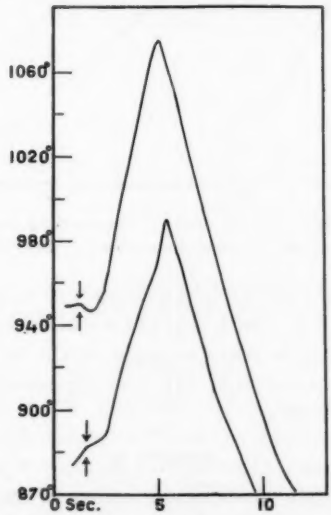

FIG. 4. *Effect I, extreme form. Thermojunction in this case was coated with paste made by mixing 0.1 percent Tb dissolved in Th, with H_2SO_4. It was then immersed in a powder of the same material in the crucible.*

pium, the other to samarium. The strong yellow band of dysprosium was also present but no band due to praseodymium was observed.

EFFECT I

The above mentioned disturbance which we may call effect I, is characterized by an abrupt rise of temperature. When terbium or uranium is the activator it starts a fraction of a second after the cessation of exposure to the flame. In the case of praseodymium the abrupt rise occurs from one to two seconds later. (See Fig. 3)

In the seventy records obtained which show effect I, the usual rise of temperature was from ten to thirty degrees, but in five instances it was much greater, *viz.*, sixty, eighty, ninety, one hundred and seven,

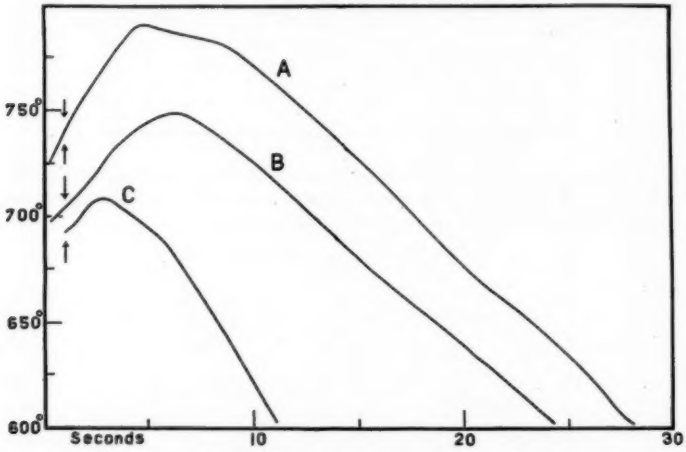

FIG. 5. *Effect II. 0.5 per cent Tb in Th, heated by Bunsen flame first below then from above. A, roaring flame. B, same, flame smooth. C, flame medium.*

and one hundred and twenty-eight degrees respectively being registered. In Fig. 4 the two last are depicted. The usual duration was from one to three seconds, running to seven seconds for the maximum value of the effect. Effect I was observed at various temperatures of flame-removal between 300°C and 1100°C.

EFFECT II

Occasionally (i.e., six times in the course of our experiments) after flame-removal a quite different type of thermal disturbances occurred. Instead of a rise of temperature abruptly superimposed upon the cooling curve and as suddenly coming to a maximum, as in effect I, the temperature rose steadily for several seconds to a maximum, then fell gradually at a rate much less than that characteristic of the normal

curve of cooling and without any visible indications of an abrupt disturbance. (See Fig. 5)

Occasionally also (observed four times) no actual rise of temperature occurred after removal of the flame, but continued heating is indicated by the form of the time-temperature curve, which instead of normal shape convex to the axes, is concave to the axes. Thus the temperature at every point is higher than in normal cooling. (See Fig. 6).

EFFECT III

In at least ten of the numerous runs made with thorium oxide activated by terbium the cooling curve indicated another marked and sudden disturbance some seconds after flame-removal and the subsidence of effect I. In one of the six records which we obtained the rise of temperature was one hundred and eighty-seven degrees (see curve *A*, Fig. 7). This disturbance, like effect I, was coincident with a sudden ruddy

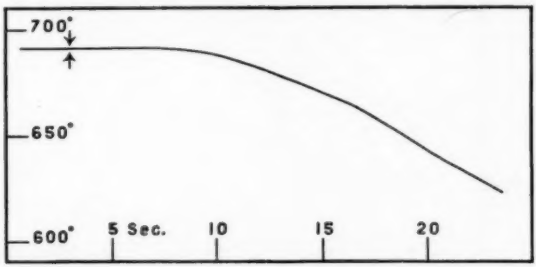

FIG. 6. *Effect II. Modification of cooling curve probably due to gradual oxidation. Same material and conditions as in Fig. 4.*

glow; but more startling because it arose after the incandescence of the cooling powder had ceased to be easily visible. It differed from effect I in that (in our experience) it could only be produced once from a given sample.

EFFECT IV

In addition to the above described effects we noticed that whenever the cooling curve of thorium oxide activated by terbium was followed to lower temperatures a succession of perturbations, abrupt and variable as to intensity, occurred between about 400° C and 150° C. These followed one another at an average interval of about five seconds. (See Fig. 8 which is a typical graph, showing twenty-four such disturbances which took place in one hundred and twenty seconds). Thirty records were made and these resembled each other closely in general character but not in detail. The maximum rise of temperature was about forty

degrees. Occasionally the start occurred just below 500° C. Similar disturbances of the cooling curve were noted in lanthanum activated by europium and in terbium dissolved in magnesium oxide, but no trace of such an effect was found when unactivated oxides were cooled.

A strong suspicion that these disturbances were due to a gradual change in the crystalline arrangement of the material within which the thermojunction was embedded was confirmed by the behavior of the galvanometer in an attempt to observe temperature changes during

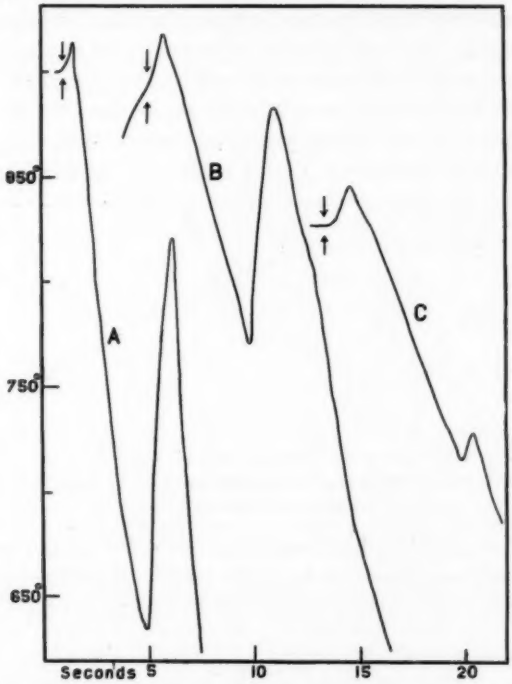

FIG. 7. *Effect III preceded by Effect I. A, 0.5 percent Tb in Th, well roasted. B, 0.1 percent Tb in Th, material powdered in mortar before use. C, 1 percent Tb in Th, material powdered in mortar before use.*

thermoluminescence. Miss Wick[3] had recently found definite temperature crests, i.e., points of maximum brightness on the intensity-temperature curves of certain fluorites containing rare earths, when these were rendered luminescent. To see whether the galvanometer would respond to these accessions of brightness the thermojunction was

[3] Wick: J.O.S.A. *21*, p. 223; 1931.

mounted in a cavity drilled in a small fluorite crystal. When heated upon an electric plate the crystal began to break up before the completion of the intended observations on thermoluminescence. Each fracture along the cleavage planes was clearly audible and produced an abrupt kick of the galvanometer. The resulting record differed from that shown in Fig. 8 only in that the disturbances were superimposed upon a curve of heating instead of upon a cooling curve. The resemblance was so striking as to lead us to ascribe the two effects to

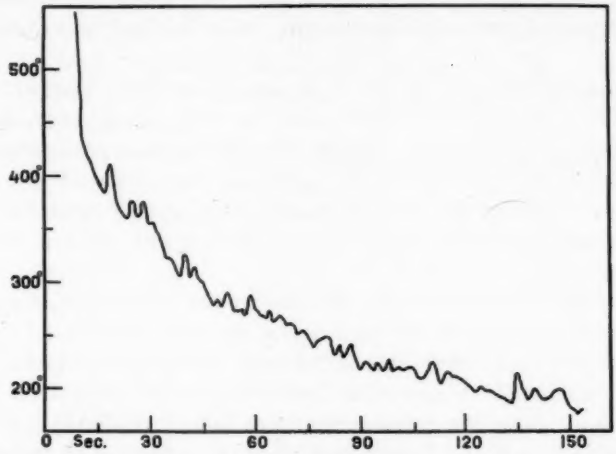

FIG. 8. *Effect IV. Disturbance due to crystallic changes. 1 percent Tb in Th, placed in "boat" at bottom of crucible, to attain (a) protection from drafts (b) protection from rapid loss of heat by conduction.*

similar causes, namely, changes in crystallographic structure. Comparison of the records leads to a further inference. When the crystal was breaking down, as in the case of the fluorite, the brief disturbances were due to sudden cooling. In Fig. 8, on the other hand, the best marked deviations indicated abrupt increases in temperature; as if minute crystals were formed spasmodically within the mass of the powder.

PROBABLE CAUSES OF EFFECTS I, II AND III

Certain of the refractory solid solvents used in the production of candoluminescence, such as the oxides of titanium,[4] tantalum,[5] colum-

[4] Nichols: Phys. Rev. [2] *22*, p. 240; 1923.

[5] Nichols, Howes, and Wilber; Publ. of Carnegie Institution, No. 384; p. 308; 1928.

bium,[6] and thorium,[7] tend to form unstable lower oxides when heated to incandescence in the reducing zone of a hydrogen flame. This change is especially noticeable in the presence of a rare-earth activator. The oxides so formed are usually dark in color, and are distinguishable by the character of their emission spectra; they tend to revert spontaneously to the higher oxide in the presence of free oxygen.

The method of heating used in our experiments is favorable to the formation of such suboxides and it is to their return to the higher form of oxidation after the removal of the flame that we ascribe the gradual development of heat which gives to the curves in Fig. 5 their distinctive form.

The curves in Figs. 3, 4, and 7, pertaining to effects I and III, seem to require a quite different explanation involving storage of energy and its sudden release: as if for example there had been an accumulation of uncombined hydrogen within the powdered material while the latter was surrounded by the flame-gases and a going into combination or perhaps rapid occlusion at a lower temperature with marked development of heat.

This surmise was strikingly confirmed by the discovery that a gentle puff of cold hydrogen gas directed against the mass of activated thorium oxide, at any time after flame withdrawal and before the powder had fallen to about 200° C, caused an immediate rise in temperature.* The resulting effect on the galvanometer was indistinguishable from that depicted in Figs. 4 and 7, save that when the current of hydrogen was

GENERAL SUMMARY

Materials studied		Effects observed
Activator	Solvent	
Terbium	in thorium oxide	I, II, III, IV, V
Praseodymium	in thorium oxide	I, V
Uranium	in thorium oxide	I,
Europium	in lanthanum oxide	I, IV
Terbium	in magnesium oxide	IV

[6] Nichols, Phys. Rev. [2], *25*, p. 376; 1925.

[7] Nichols and Boardman: J.O.S.A. *20*, p. 115; 1930.

* These experiments were suggested by the unexpected rise of temperature produced when the stream of gas from an *unlighted* Bunsen burner was inadvertently pointed towards a heated mass of activated thorium oxide. A similar effect had been noted in the early development of the Welsbach mantel. It was studied by Luggin whose experiments were described by Bunte (Journal für Gasbeleuchtung XLIV p. 411; 1901).

maintained the temperature continued to rise until at about 800° C the hydrogen became ignited. Further studies of the phenomenon are in progress.

CAUSES SUGGESTED

Effect I. Reduction of the material by the flame and its immediate oxidation after removal (Fig. 3); or storage of free hydrogen by the material while within the flame and its sudden release and oxidation after removal (Fig. 4).

Effect II. Production of suboxides or storage of free hydrogen while within the flame and gradual oxidation after removal. (Figs. 5 and 6).

Effect III. *Belated* release and oxidation of hydrogen by the substance while within the flame.

Effect IV. Crystallographic rearrangements of the cooling substance.

Effect V. Storage and subsequent oxidation of cold hydrogen supplied from without after removal of flame.

REVIEW

Photogrommetrie und Luftbildwesen. By R. Hugershoff, Vol. VII Handbuch der Wissenschaftlichen und Angewandten Photographie, Alfred Hay editor, 264 pp. Julius Springer, Vienna. 1930.

The art and science of photographic mapping, especially aerial mapping, has developed rapidly in recent years and gained correspondingly in practical importance. Volume VII of the Handbuch der wissenschaftlichen und angewandten Photographie deals very adequately with this subject. The author of this volume has contributed materially to the development of this art, and to the equipment used by those who practice it. Modern methods and equipment can hardly be described without mentioning his name. The volume is therefore the product of a competent authority.

The volume will appeal equally to those interested in the underlying principles and those interested in practical details. A very brief historical introduction is followed by a lucid exposition of the field of application and the advantages of photographic methods of mapping. Subsequent chapters deal in logical order with the problems to be met and available methods for handling them. Sources of error and the factors limiting the accuracy are adequately discussed. The final chapter deals with the technique of photographic mapping from aircraft.

The volume is written in a clear and concise manner and the illustrations are adequate both as to quality and quantity. It should be a satisfactory reference book or working guide to anyone devoting appreciable time to this subject.

E. A. Eckhardt

DR. PAUL D. FOOTE
Editor, 1920–1932

EDITORIAL

The Retirement of Dr. Paul D. Foote as Editor-in-Chief

On September first, Dr. Paul D. Foote retired as Editor-in-Chief of the Journal of The Optical Society of America and of The Review of Scientific Instruments, after having completed nearly 13 years of service. Since their very inception, Dr. Foote has done so much for these journals, and has guided them so wisely through the many difficulties which ever confront scientific publications, that a chronicle of Dr. Foote's services as Editor-in-Chief is almost synonymous with a history of the publications of the Optical Society of America.

Immediately after its organization, the Optical Society of America made plans for the publication of an official organ. The first number of the Journal of The Optical Society of America appeared in January, 1917, with the late Dr. Hermann Kellner as Editor. The entry of the United States into the war interrupted all scientific work and in consequence only six numbers of the new journal were issued during the three years 1917–1919.

Late in 1919, upon the resignation of Dr. Kellner, Dr. Foote, at that time physicist at the Bureau of Standards, was appointed Editor, and was assigned to the duty of starting the Journal anew. The first number under his editorship appeared in January, 1920, as Volume IV, No. 1, and during 1920 and 1921 was issued bi-monthly. Partly because it filled an important need, but more particularly because of Dr. Foote's wise editorial policy, the Journal won instant recognition. Volumes IV and V contain over 1000 pages of articles on optics in its various branches.

In 1922 the Journal was enlarged by adding, in collaboration with the Scientific Apparatus Makers of America, a section devoted to scientific instruments, the name of the Journal being changed to the Journal of The Optical Society of America and Review of Scientific Instruments. The editorial board was reorganized with Dr. Foote as Editor-in-Chief and a schedule of monthly publication was adopted. Due to the high standards which Dr. Foote maintained in conducting the enlarged journal, it made rapid progress and soon became one of the world's recognized journals in physics and related fields. The separation of the combined journal into the two journals, Journal of The Optical Society of America and The Review of Scientific Instruments, in 1930, was a natural step after the value of the section on scientific instruments had been demonstrated.

During the thirteen years of Dr. Foote's editorship he has personally supervised the publication of over 15,000 pages of text,—a task which, as those who have had experience know, has demanded very heavily of his time and energy. To have been thus instrumental in starting and in conducting for a long period of years two important scientific journals, is an achievement of which any one may be proud. On behalf of his colleagues on the editorial board, and of the many readers of the JOURNAL OF THE OPTICAL SOCIETY OF AMERICA and of THE REVIEW OF SCIENTIFIC INSTRUMENTS we wish to take this occasion to express to him our sincere appreciation of his untiring energy and of his devotion to the editorial work which he has so ably done. We regret that his duties as Director of the Research Laboratories of the Gulf Companies make it impossible for him to continue with us. But we shall hope that the standards which he set shall be maintained, and that the JOURNALS shall continue to prosper.

F.K.R.